Maintaining Infrared Exoplanet Transit and Eclipse Measurement Capability in the Post JWST Era

Astro2020 APC White Paper

Type of Activity: Project, Space-Based

Principal Author:

Mark Swain
Jet Propulsion Laboratory, California Institute of Technology
Pasadena, CA
Mark.R.Swain@jpl.nasa.gov
818-455-2396

Co-authors:

Mike Werner (JPL), Gautam Vasisht (JPL), Clara Sousa-Silva (MIT), Renyu Hu (JPL)

Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

ABSTRACT

Infrared measurements between 1 and 5 μm, obtained with Hubble and Spitzer, have played a transformative role in our understanding of exoplanet atmospheric composition, heat flow, and global radiation balance. Even given successful coronagraphic/starshade measurements, there will be many science questions and targets where transit spectroscopy measurements provide the best option for scientific progress. In planning future flagship-class missions, we strongly advocate for maintaining this important scientific capability, which is needed to fully exploit the science opportunities arising from the new planets discovered by the TESS, PLATO, and CHEOPS missions. Current studies of flagships like HABEx and LuVOIR typically have a long wavelength limit around 2 μm and could include exoplanet transit measurements out that limit, but we argue to extend the capabilities to 5 μm explicitly for exoplanet studies. Large, flagship-class missions with 1-5 μm measurement capability may be able to probe the atmospheres of habitable zone planets with broader wavelength coverage than will be possible with direct imaging methods. The broader wavelength coverage possible with transit observations is well suited for simultaneous detection of both oxidized and reduced species, which has been identified as a potentially important diagnostic of biological activity. Werner et al. 2016 studied the implementation of 1-5 μm capability on a warm space-based telescope, which examines the science and technical issues in greater detail than is possible in this white paper. The work by Werner et al. 2016 shows that implementing 1-5 μm capability for exoplanet observations does not require a cold telescope and that a fiber-coupled, passively cooled instrument can enable the rest of the payload to be warm. Here we advocate for including 1-5 μm spectroscopic capability on future flagship-class mission concepts even if the telescope itself is not cooled.

1 KEY SCIENCE GOALS AND OBJECTIVES

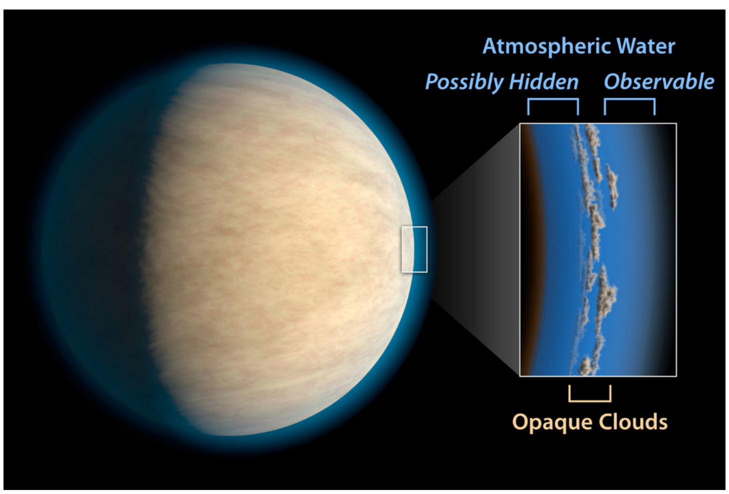

Figure 1: Transit spectroscopy has probed the terminator region of numerous planets and showed that water and aerosols are both common by virtue of the muted water spectra typically detected. Image credit: NASA/JPL-Caltech

Since the first detection of exoplanet atmospheres (Charbonneau et al. 2002), space-based observations of transiting exoplanets have profoundly shaped our understanding of these worlds that orbit other stars. Here "transiting exoplanet observations" describes any observations of a transiting exoplanet system, including [secondary] eclipse and phase curve measurements as well as transit measurements per se. Within this envelope, specific subcategories of observations exist, differentiated by the portions of the light curve sampled, which yield different kinds of information about the exoplanet. While this document focuses specifically on the need for future space-based infrared capability for observing exoplanets, ground-based observations (e.g. Redfield et al. 2007, Snellen et al. 2010) have participated in transiting exoplanet science and are complementary to space-based observations. Currently, the community eagerly looks forward to continued observations of transiting exoplanets with Hubble, followed by what is widely anticipated as spectacular results from JWST observations. At the time of this writing, JWST has plans to observe 26 transiting exoplanets in guaranteed time observations (GTO) and many more in community early release science (ERS). In this manuscript, we advocate for continuing to provide the important infrared transit observational capability after JWST ceases operations.

While large ground-based telescopes may be capable of transit measurements out to 5 μm, space-based observations, even with a warm telescope, have significant advantages. These include: access to the entire infrared spectrum, including the molecular species in the Earth's atmosphere which will be of particular interest; stability and sensitivity; and clear skies and long observations, so that measurements requiring many hours of observation can be reliably scheduled and executed. While the mission concepts LUVOIR and HABEX advocate including instrumentation operating out to 2.0-2.5 μm which can do transit studies, we are specifically advocating for the importance of extending this spectral coverage to 5 μm because of the many molecular species that are strong absorbers in the region. Table 1 lists molecules that are potentially detectable with 1-5 μm transit spectroscopy measurements. Four of these molecules, H_2O, CH_4, CO_2, and CO are key diagnostics because they trace major reservoirs of oxygen and carbon in planetary atmospheres. Of these four key diagnostic species, CH_4, CO, and CO_2 all have strong bands between 2.5-5 μm and are thus far easier to detect and quantify with spectral coverage that includes the 2.5-5 μm interval.

Table 1: A non-exhaustive list of potential transit-detectable molecules and locations of their prominent bands.

	Molecule	1.0–2.5 μm	2.5–5.0 μm
Key Diagnostic Molecules	H_2O	1.13, 1.38, 1.9	2.69
	CH_4	1.65, 2.2, 2.31, 2.37	3.3
	CO_2	1.21, 1.57, 1.6, 2.03	4.25
	CO	1.57, 2.35	4.7
Additional Possible Molecules	C_2H_2	1.52	3.0
	HCN		3.0
	O_3		4.7
	O_2	1.27	
	NH_3	1.5, 2, 2.25, 2.9	3.0
	C_2H_4		3.22, 3.34
	C_2H_6	1.95, 2.3, 2.6, 2.95	3.07, 3.34
	H_2S	2.5	3.8
	SO_2		4
	N_2O	2.8	3.9, 4.5
	TiO	1.0–3.0	3.0–3.5
	VO	1.0–2.5	

Additionally, the 2.5-5 μm is where many strong rovibrational modes of dozens of atmospheric molecules are spectrally active. It is where the fundamental, as well as excited and combination, bands fall. Consequently, the ability to not just identify these molecules, but distinguish them from other gases with similar spectral features, requires the detection of multiple features for each relevant molecule, which in turn requires a larger wavelength coverage. without the 1-5 μm region, the identification of crucial atmospheric species is vulnerable to incorrect assignments, false positives, and false negatives. The unambiguous detection of most molecules requires access to multiple features, covering a wide spectral region.

Space-based, infrared observations of transiting exoplanets have enabled a series of spectacular scientific results, which we illustrate by summarizing selected highlights corresponding to observations that focus on different portions of the orbit. Some of the earliest high-impact infrared transiting exoplanet measurements were eclipse observations conducted with Spitzer that detected the first thermal emission from an exoplanet atmosphere (Charbonneau et al. 2005, Deming et al. 2005). This was followed by more Spitzer eclipse observations reporting the first spectroscopic detection of an exoplanet emission spectrum (Grillmair et al. 2007) and the first reported detection of a stratosphere (Knutson et al. 2008). Transit observations by Spitzer and Hubble, which provide terminator region

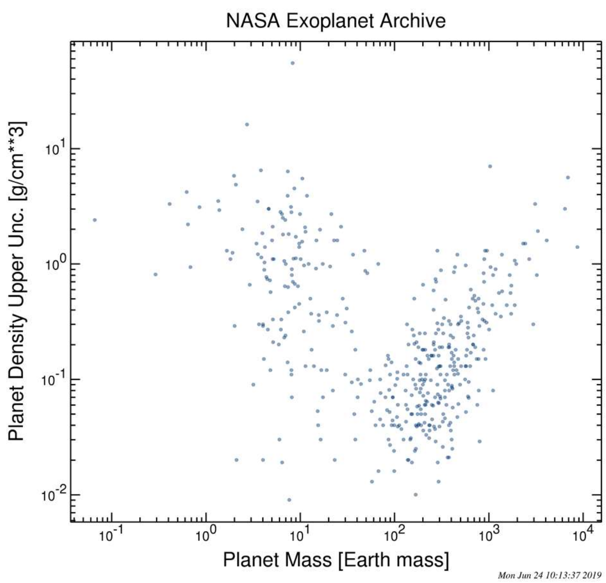

Figure 2: Visualizing the remarkable diversity of exoplanets in terms of bulk density, which is a product of transiting planet measurements where the radius is determined.

limb transmission measurements, reported the detections of molecules in an exoplanet atmosphere, first with photometry (Tinetti et al. 2007) and then with spectroscopy (Swain et al. 2008). Over the course of several years, community observations using the Hubble WFC3 near-infrared spectral capability went on to show that water is common in exoplanet atmospheres, as are clouds and aerosols (Sing et al. 2016, Iyer et al. 2016, Stevenson 2016 – see Figure 1 which illustrates how transit spectroscopy measurements have revealed the presence of both water and aerosols in exoplanet atmospheres). Similarly, community observations of numerous exoplanets with IRAC in the Spitzer warm mission have been used to infer atmospheric circulation and albedo constraints (Schwartz & Cowan 2015). Spitzer observations of exoplanet phase curves have shown hot spot advection due to powerful zonal winds (Knutson et al. 2007) while spectral phase curve observations with WFC3 have shown an altitude dependence of hot-spot longitude (Stevenson et al. 2014). In a spectacular demonstration of what we can look forward to with James Webb, Spitzer thermal emission observations, concentrating on the eclipse ingress and egress portions of the light curve, demonstrated the first low resolution image of an exoplanet (Majeau et al. 2012). The selected infrared observations of transiting exoplanets we have highlighted here represent only a small portion of what has developed into one of the most scientifically productive and exciting areas for studying exoplanets. While ground-based observations have participated in infrared observations of transiting exoplanets (e.g. Snellen et al. 2010), correcting telluric contamination has proved difficult, and the bulk of the scientific results have come from space-based infrared observations of transiting exoplanet systems.

The scientific potential of studying transiting exoplanets, due to knowledge of the planet radius, has long been recognized (Charbonneau et al. 2000). When combined with mass determinations through radial velocity measurements or transit timing variations, studies of transiting planets allow determining a planet's bulk density (see Figure 2) that, in turn, allows the study of a wide range of exoplanet topics; some examples of this include the influence of the planet formation process on composition (e.g. Mordasini et al. 2016, Thorngren et al. 2016, Espenoza et al. 2017), atmospheric and envelope evolution (e.g. Owen & Wu 2013, Lopez & Fortney 2013, Owen & Wu 2017, Ginzburg et al. 2018, Gupta & Schlicting 2019), and internal heating (e.g. Batygin & Stevenson 2010, Thorngren & Fortney 2018) e.g. inflated hot-Jupiters. A perhaps even more exciting aspect of the scientific potential of transiting planets is the potential for identification of terrestrial planets in the habitable zone with the intent for detailed follow-up observations to characterize the atmospheres of these potentially habitable worlds; this potential has been spectacularly demonstrated with the Trappist-1 system (Grimm et al. 2018), and recent work shows that TESS will be sensitive to planets in the habitable zone for more than 200 nearby stars (Kaltenegger et al. 2019). Collectively, the science topics enabled by transiting exoplanets have led to numerous space missions and ground-based projects to identify transiting exoplanets (see Table 2). As a community, we will have a large number of planets that we will want to characterize. Many of them will be potentially habitable and we will not want to miss the opportunity to interpret their atmospheres as completely as possible. This can only be done by spectroscopic follow-up with broad-wavelength coverage.

Table 2: Missions and Projects to Identify Transiting Exoplanets[1]

Location	Name	Launch year or status	Planets found
space	CoRoT	2006	29
	Kepler	2009	2342
	K2	2016	360
	TESS	2018	30 [2]
	CHEOPS	2019	--
	PLATO	2026	--
ground	HAT(S)	active	109
	KELT	active	20
	MASCERA	active	2
	MERTH	active	2
	NGTS	active	3
	QES	active	9
	SPECULOOS	commissioning	--
	Super WASP	active	157
	Trappist	active	7
	TrES	decommissioned	5
	XO	active	5

[1]https://en.wikipedia.org/wiki/List_of_exoplanet_search_projects#Ground-based_search_projects
[2] TESS ~2500 planets expected for full mission

The scale of the world-wide effort in identifying transiting exoplanets is truly impressive. If we only consider the major NASA and European missions, the investment is of the order more than a billion dollars. These missions, collectively, along with ground-based follow-up programs, will find several thousand exoplanets. Following up new discovery of transiting exoplanets with detailed studies of their atmospheres using the transit method is an extremely exciting science opportunity. While continuing to make extensive use of Hubble and Spitzer, the exoplanet transit community eagerly awaits the NASA JWST mission and the ESA M4 ARIEL (Atmospheric Remote-sensing Infrared Exoplanet Large-survey) mission. The remarkable exoplanet science potential for JWST is widely recognized (e.g. Seager et al. 2008, Beichman et al. 2014, Cowan et al. 2015) and is enabled by a combination of broad spectral coverage, improved spectral resolution with respect to HST instruments, and large collecting area. Likely reflecting the broad interest and potential for highly impactful science, the largest JWST community ERS (Early Release Science) award (75 hours) was made to the exoplanet community (Bean et al. 2018). Additionally, there are 26 transiting exoplanets that are part of the JWST GTO (Guaranteed Time Observations) program. Beyond a doubt, JWST will have a major scientific impact on the study of exoplanet atmospheres. Following JWST, the community can look forward to the statistical survey of approximately 1000 exoplanet atmospheres by the ARIEL mission (e.g. Edwards et al. 2019). Critically, both JWST and ARIEL will have broad spectral coverage from visible wavelengths into the thermal infrared (0.5-7.8 μm). The broad spectral characterization capability of JWST and ARIEL is critical for characterizing exoplanet atmospheres (Sing et al. 2016, Greene et al. 2016) because it removes model degeneracies that are present when fitting spectra with restricted range (see for example the discussion in Kreidberg et al. 2015), allows accurate temperature determination for a wider range of exoplanet temperatures, and enables the unambiguous identification of many potential biosignature gases requires the detection of multiple spectral features for each molecule, which is only possible with infrared coverage; the same arguments for 1-5 μm spectral coverage apply to our proposal in this white paper. While ARIEL is a dedicated mission for the study of exoplanet atmosphere, as a 3.5-year mission with a 1-meter class telescope, it cannot offer the ability for detailed characterization of small planets that is possible with the large aperture of a flagship- class mission. The critical question facing the US community is what kind of transit spectroscopy capability will be available in the post JWST era?

Scientific continuity with previous work is essential for transit spectroscopy. Following up the discovery of new transiting exoplanets with infrared measurements is a large-scale and critical part of the exoplanet science community, and their efforts have provided the majority of what we know about exoplanet atmospheres. There will be many more planets detected with TESS than can be followed up by JWST alone. Additionally, PLATO, launching in 2026, will find thousands more with greater sensitivity to longer period planets and (similar to TESS) specifically targeting bright host stars. The exoplanet community will have a compelling need to follow up these targets in the post JWST era. The availability of Hubble and Spitzer, succeeded by JWST, has and will continue to give the US community the ability to characterize exoplanets from the visible (uniquely sensitive to clouds and hazes) to ~5 μm, the near-thermal infrared, encompassing strong bands of CO, CO_2 and CH_4. Without semi- continuous coverage of wavelengths from the visible to ~5 μm, our ability to determine the chemical state of exoplanet atmospheres will be limited. This coverage can be especially important when characterizing potentially habitable worlds where we need to simultaneously detect, unambiguously, both oxidized and reduced species to avoid false positive biosignatures (e.g., Hu et al 2012, Domagal-Goldman et al. 2014, Lugar & Barnes 2015, Meadows et al. 2018). The potential for transit spectroscopy to characterize habitable exoplanets is substantial; several of the currently known transiting exoplanets are located in the habitable zone, and TESS is predicted to find of order 20 habitable zone planets (Sullivan et al. 2015). Current and upcoming missions will detect many potentially habitable planets and our ability to characterize them will be compromised unless we can observe them across a wide spectral region.

Through the combination of Hubble and Spitzer, the 1-5 μm measurement capability has been essential to our current understanding of exoplanet atmospheres, and JWST will offer improved spectral resolution and sensitivity in this critical spectral region. In the post JWST era, continuity of capability between 1-5 μm is essential for following up planets identified by PLATO, some of which will certainly be in the habitable zone. Another reason to advocate for 1-5 μm capability is that the study of exoplanet atmospheres is a rapidly evolving area and new science themes continue to emerge. An example of a relatively new theme is the super-Earth/sub-Neptune transition region, which exists for planet radii around R_{planet} ~1.75 $R_\oplus$, and which is associated with a decrease in planet occurrence rate attributed to envelope loss (Fulton et al. 2017, Swain et al. 2019). The super-Earth/sub-Neptune transition reigion is emerging as an important area for additional study because of the potential for forming Terrestrial planets either by accretion of smaller solids or by envelope loss (see Figure 3). Detailed atmospheric characterization of these small planets is a task well suited to large-aperture space observatories such as JWST or a future Flagship-class mission. Already, numerous examples are known of these planets with radii ~1.75 $R_\oplus$ and the combination of TESS and PLATO will find even more. Further, the super-Earth/sub-Neptune transition region can potentially contain planets with reduced mean molecular weight atmospheres (Hu et al. 2015), which, in turn, acts to increase the atmospheric scale height and thus makes spectral features easier to study with the transit method.

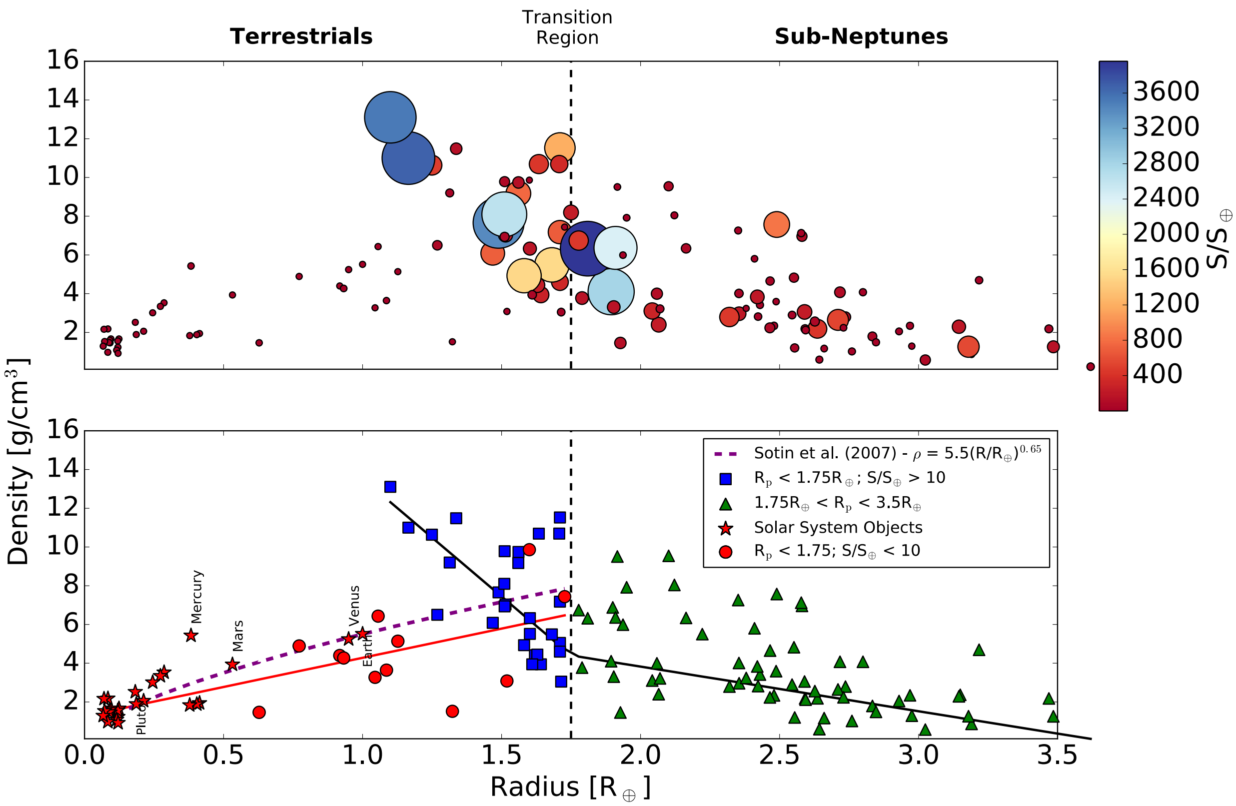

Figure 3: Terrestrial planets can be separated into two families (red and blue above), based on insolation, one of which is likely the remnant bare cores of sub-Neptune planets (Swain et al. 2019). Terrestrial planets that formed from sub-Neptunes can retain a small fraction of the original envelopes (Hu et al. 2015), potentially causing a reduction in atmospheric mean molecular weight and improving observability of molecular features.

2 TECHNICAL OVERVIEW

There is sometimes a concern that 1-5 μm observational capability requires a cold telescope. However, in the case of bright point sources, this is not the case because the photon noise dominates the thermal background from the telescope.

For exoplanet transit science, the implementation of 1-5 μm spectroscopic capability on a future NASA Flagship-class mission can be done using a warm telescope (Werner et al. 2016). For many observations of planets transiting bright stars, which will be the prime targets for study, and which will be discovered by TESS and PLATO, the fact that the

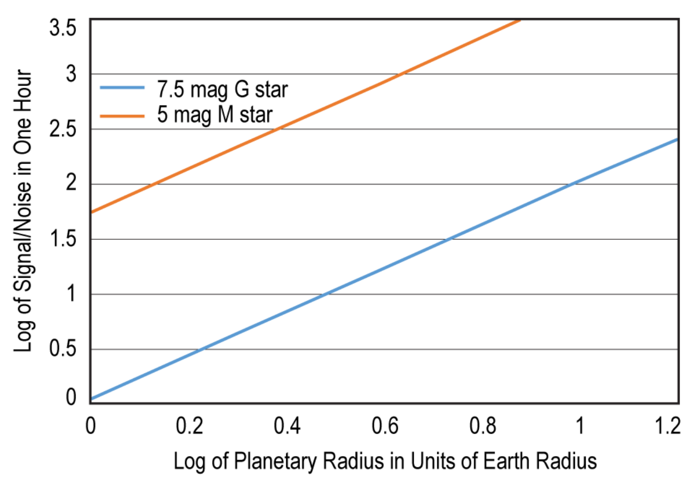

Figure 4: Signal to Noise Ratio (SNR) for each resolution element on the transit in 1 h for planetary transits at 4 μm. A 9.2 m 293 K telescope and R=200 fiber-fed spectrograph (Werner et al. 2016 main body and Appendix).

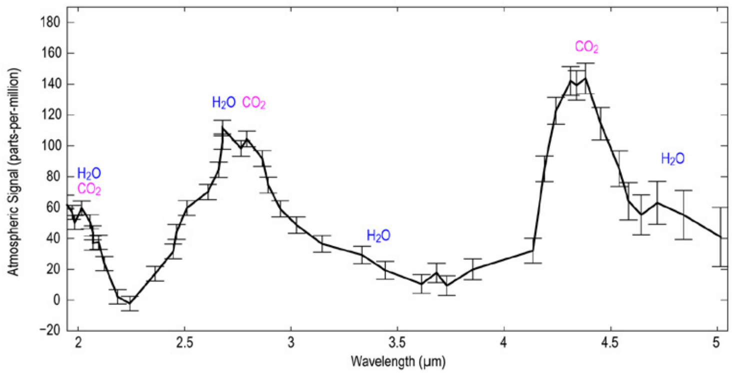

Figure 5: An illustration from Werner et al. 2016 showing a hypothetical water (80%) and CO_2 (20%; mean molecular weight of 23) sub-Neptune planet transiting a M4V star (15 pc). This planet has a radius of 2.7 R_{Earth}, a mass of 6.5 M_{Earth} and an atmospheric temperature ~500 K. Error bars indicate the 1-sigma precision that could be obtained along the spectrum per R=100 spectral bin in 6 hours, which would typically require a few transits.

telescope is warm is not relevant, because the limiting noise will be stellar photon noise, not the thermal background. As one possible implementation, Werner et al 2016 describe a fiber fed spectrograph optimized for exoplanet studies which could be effectively used on warm telescope. It uses a prism disperser to cover the 1-5 um wavelength range with R~200. Notionally, the input slit[s] would be in the focal plane of an ambient temperature telescope and the image carried by fiber to the spectrograph, which would sit at the edge of the telescope/instrument enclosure at a position where radiative cooling could supply the required detector temperature. The spectrometer package can be accommodated in a 10 cm cube (equivalent to a 1U cube sat size). Two examples of the estimated performance of this instrument on a warm telescope are given in Figure 4 that shows for bright stars, transit measurements will readily achieve S/N>100 as required for studying atmospheric features. For a given star/planet pair, the measurement during eclipse will have lower signal to noise, but may frequently be high enough to permit the critical determination of the temperature of the planet, even if the resolution has to be degraded somewhat.

An example of the spectra enabled by this instrument is illustrated in Figure 5, showing the spectrum achieving a resolution $\lambda/\Delta\lambda = 100$ in 6 hours of observations. In the limit where stellar photon noise is the main noise source, the temperature of the telescope is not a limiting factor. This is illustrated in Figure 6, which shows how the sensitivity achievable with this spectrograph on a large, warm telescope compares with that predicted to be realized with the infrared spectrograph on JWST. As the figure suggests, for example, for stars brighter than ~8^{th} magnitude at L band the stellar photon rate exceeds the thermal background from a 10-m class room temperature telescope with emissivity ~20%, showing that there is no penalty for observing transits and eclipses with a warm telescope. Again, we note that exoplanets orbiting the brightest host stars will de facto become the most interesting targets to study; these are the targets for which the very best measurement precision can be obtained using the transit method.

3 TECHNOLOGY DRIVERS

None. There are no technology drivers for this concept. The study baselined currently available optics and detector technology operating with passive cooling.

4 ORGANIZATION, PARTNERSHIPS, AND CURRENT STATUS

None currently. We are advocating that the 2-5 μm spectral capability be studied for inclusion on the next NASA flagship-class mission for uvoir astronomy.

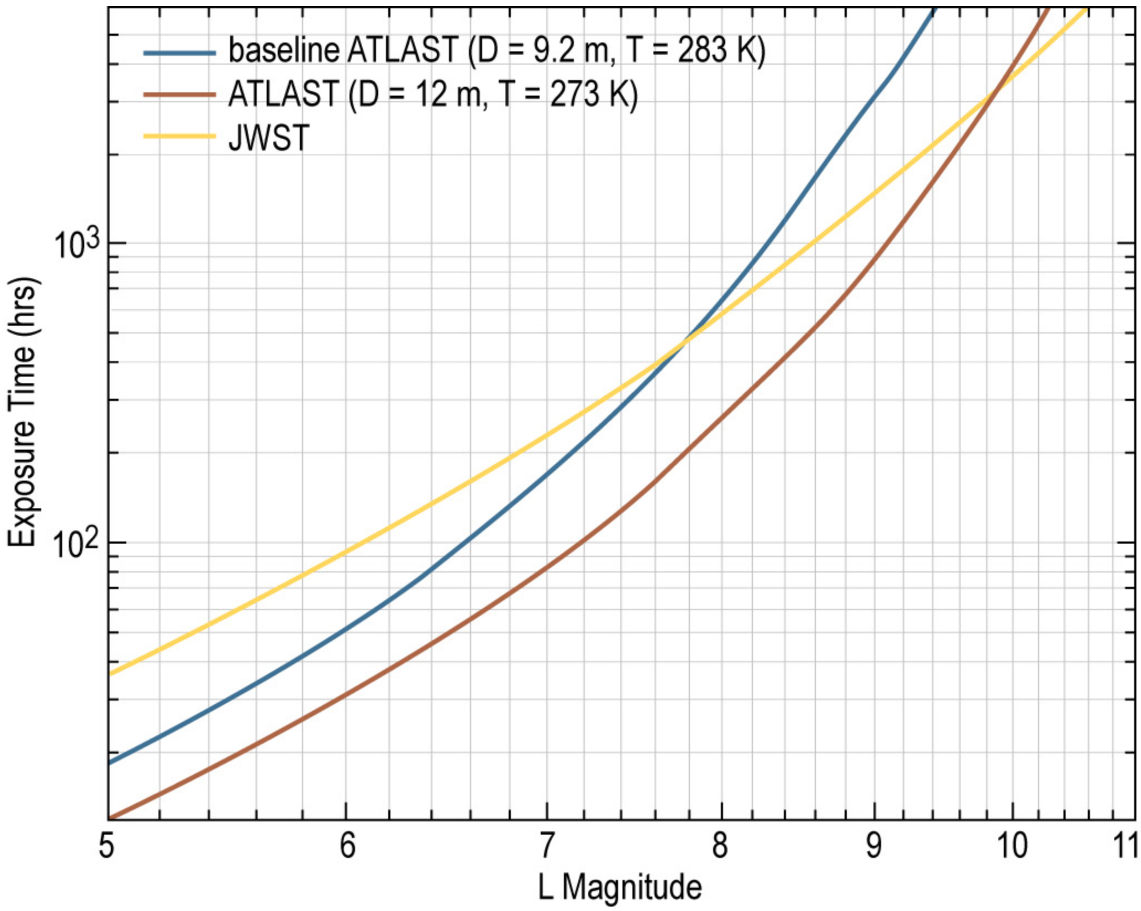

Figure 6: A comparison from Werner et al 2016 showing the time taken for three telescope configurations to achieve a SNR = 5 detection of a 10 ppm spectral feature with spectral width ($\lambda/\Delta\lambda$ = 200) at 4 μm due to a transiting exoplanet as a function of the L band stellar magnitude. For bright exoplanet host stars, a warm 12 meter telescope would take approximately 4 times less time than JWST to make the same observations, and a 9.2 meter telescope about half the time.

5 SCHEDULE

To be determined by the flagship-class mission pre-phase A formulation schedule.

6 COST ESTIMATES

We have no specific cost estimate. However, the concept 1-5 μm dispersive (R=200) spectrometer that was studied could be implemented in a 10 cm cube, and could be coupled to the warm telescope focal plane by a fiber to facilitate passive radiative cooling of the detector and cold front end electronics. Mass and power requirements in this configuration are low corresponding to a few kilograms and less than a watt of power. Absent a direct cost estimate we refer to the IRS flown on Spitzer, which cost $48M through launch and on orbit checkout. The IRS consists of four modules, each of which is roughly comparable in size and complexity to our simple spectrograph discussed in this white paper. Allowing for some economy of scale and non-recurrent engineering, we estimate that the first module cost no more than $25M. Even allowing for the 1.5x inflation from the IRS peak spending year of 1999 to now, we feel that the spectrometer described here, similar in scale and scope to an individual module of the IRS, could be built for less than $50M.

7 REFERENCES

Batygin & Stevenson 2010 ApJ, 714L 238B
Bean et al. 2018 PASP, 130k, 4402B
Beichman et al. 2014 PASP, 126, 1134B
Charbonneau et al. 2000 ApJ, 529L, 45C
Charbonneau et al. 2002 ApJ, 568, 337C
Charbonneau et al. 2005 ApJ, 626, 523C
Cowan et al. 2015 PASP, 127, 331C
Deming et al. 2005 Nature, 434, 740
Domagal-Goldman et al. 2014 ApJ, 792, 90D
Edwards et al. 2019 AJ, 157, 242E
Espinoza et al. 2017 ApJ, 838L, 9E
Fulton et al. 2017 AJ, 154, 109F
Ginzburg et al. 2018 MNRAS, 476, 759G
Greene et al. 2016 ApJ, 817, 17G
Grillmair et al. 2007 ApJ, 658L, 115G
Grimm et al. 2018 A&A, 613A, 68G
Gupta & Schlicting MNRAS, 487, 24G
Hu et al. 2012 ApJ, 761, 166H
Hu et al. 2015 ApJ, 807, 8H
Iyer et al. 2016 ApJ, 823, 1091
Kaltenegger et al. 2019 arXiv:1903.11539
Knutson et al. 2007 Nature, 448, 143K
Knutson et al. 2008 ApJ, 673, 526K
Lopez & Fortney 2013 776, 2L
Luger & Barnes 2015 AsBio, 15, 119L
Majeau et al. 2012 ApJ, 747L, 20M
Meadows et al. 2018 AsBio, 18, 630M
Mordasini et al. 2016 ApJ, 832, 41M
Owen & Wu 2013 ApJ, 775, 105O
Owen & Wu 2017 ApJ, 847, 29O
Redfield et al. 2008 ApJ, 673, 87R
Schwartz & Cowan 2015 MNRAS, 449, 4192S
Seager et al. 2008 ASSP, 10, 123S
Sing et al. 2016 Nature, 529, 59S
Snellen et al. 2010 Nature, 465, 1049S
Stevenson et al. 2014 Science, 346, 838S
Stevenson 2016 ApJ, 817L, 16S
Sullivan et al. 2015 ApJ, 809, 77S
Swain et al. 2008 Nature, 452, 329S
Swain et al. 2019 ApJ, accepted
Thorngren et al. 2016 ApJ, 831, 64T
Thorngren & Fortney 2018 ApJ, 155, 214T
Tinetti et al. 2007 Nature, 448, 169T
Werner et al. 2016 JATIS, 2d, 1205W